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Characterization of amorphous magnetic materials under high-frequency non-sinusoidal excitations

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Abstract

In power electronic based energy conversion, the high-frequency transformer (HFT) is usually excited with a high-frequency (HF) square wave voltage generated from a power electronic converter circuit (PEC). A PEC needs a reasonable dead-band (DB) and the inclusion of the DB changes the shape of the square wave. In this paper, for the characterization of the core, the DB is varied to produce different non-sinusoidal excitation voltages and an optimized excitation voltage is identified. The effect of the DB on the hysteresis loop of the HFT is also demonstrated. The mathematical analysis shows that the inclusion of the DB causes the core loss to decrease for a fixed excitation voltage and frequency. However, an increased DB produces a higher distortion at the output voltage and the current of HFT. Therefore, an optimized DB is mandatory to minimize the core loss and the distortion at the same time. Additionally, the specific loss scenario of the core under the HF triangular and trapezoidal wave voltage excitation is investigated. To validate the findings, an optimized core is simulated in COMSOL Multiphysics software and a prototype core is developed in the laboratory using the amorphous magnetic material.

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ABSTRACT

In power electronic based energy conversion, the high-frequency transformer (HFT) is usually excited with a high-frequency (HF) square wave voltage generated from a power electronic converter circuit (PEC). A PEC needs a reasonable dead-band (DB) and the inclusion of the DB changes the shape of the square wave. In this paper, for the characterization of the core, the DB is varied to produce different non-sinusoidal excitation voltages and an optimized excitation voltage is identified. The effect of the DB on the hysteresis loop of the HFT is also demonstrated. The mathematical analysis shows that the inclusion of the DB causes the core loss to decrease for a fixed excitation voltage and frequency. However, an increased DB produces a higher distortion at the output voltage and the current of HFT. Therefore, an optimized DB is mandatory to minimize the core loss and the distortion at the same time. Additionally, the specific loss scenario of the core under the HF triangular and trapezoidal wave voltage excitation is investigated. To validate the findings, an optimized core is simulated in COMSOL Multiphysics software and a prototype core is developed in the laboratory using the amorphous magnetic material.

I. INTRODUCTION

In recent years, high-frequency transformers (HFTs) are becoming promising especially for use in solid state transformer,[1] and dc-dc and multiport power converters[2] due to their widespread applications in renewable based power generation. The use of amorphous and nanocrystalline magnetic materials have received significant interest for their unparalleled property of high magnetic induction, high efficiency, and low specific core loss.[3,4] In power applications, the HFTs usually operate under non-sinusoidal excitations and the core performance changes with the change of excitation waveforms. Also, the power conversion losses highly depend on the design of HFT. The characteristics of the newly developed magnetic materials under different non-sinusoidal excitations and optimized power conversion scenarios with those materials are still not well investigated. Traditionally, the grain oriented silicon sheet steels have been used for power frequency transformers, which are not suitable for high-frequency (HF) applications due to heavy eddy current losses.[4] For the HF inductors and transformers, soft ferrites have been commercially utilized due to their low cost and high availability.[5] However, their maximum flux density is very low (from 0.3T to 0.5T), which may cause the core to be heavy and lossy for high power applications. In comparison to the amorphous materials, the nanocrystalline materials offer less loss. However, the amorphous materials have a higher flux density property (1.56 T) than that of the nanocrystalline materials (1.2 T). Therefore, in this paper, for the development of the core and the experimental investigation, the amorphous magnetic material is chosen.

In the previous literatures, different loss analysis techniques and mathematical expressions have been investigated under HF non-sinusoidal excitations. The nanocrystalline core is experimentally characterized for 500 kHz and an empirical core loss calculation method is presented for resonant converter applications.[6] The authors show that with a fixed peak flux density, the core loss increases with the decrease of the duty cycles for square wave signals.

An improved core loss calculation method has been proposed, where the relaxation effect of the magnetic material is taken into account.[7] The core loss expressions for the three-level voltage profiles in the case of a medium frequency transformer based isolated dc-dc converter are also investigated.[8] None of the above papers considered the overall effect of the DB from the high-frequency inverter on the core loss of the HFT. In this paper, the amorphous magnetic material based magnetic core is characterized and explored under different non-sinusoidal excitations. The core loss expression due to the inclusion of the DB is derived based on the modified Steinmetz equation (MSE).[9] It is expected that the paper could be a good reference for the design of an optimal HFT using advanced magnetic materials.

II. ANALYSIS OF THE DEAD-BAND EFFECT ON THE CORE LOSS

For the analysis of the DB effect on the core loss, it is assumed that the core is excited with a HF square wave voltage, generated from the HF inverter. By varying the DB, different non-sinusoidal waveforms can be generated. If a certain amount of DB is included in the square wave signal, the corresponding flux density signal will not be a pure triangular signal, rather it will take a trapezoidal shape. The amplitude and time period of the excitation voltage is V_{dc} and T respectively. The use of the parameter x $(0 < x \leq 1)$ is an alternative approach to indicate the amount of the DB inclusion. Hence, the DB will be zero if x becomes 1.0 and the DB will increase if x decreases. According to the MSE method, after inclusion of the DB, the expression for the core loss (watt/m^3) calculation can be derived as:

$$P = k_h \left(\frac{x V_{dc}^2}{2\pi^2 A^2 N^2} \right)^{\alpha-1} f_r^{2-\alpha} B_m^{2(1-\alpha)+\beta} \tag{1}$$

where, A and N define the cross sectional area of the core and number of turns respectively. The peak of the flux density signal is B_m and f_r is the frequency of the excitation voltage. The parameters k_h, α, and β are the Steinmetz coefficients and can be found from the manufacturer data sheets. By varying the parameter x, different excitation voltage signals can be found. Equation (1) shows that the core loss depends on x, if other parameters are held constant. Therefore, the core loss will be decreased if x is decreased and vice versa. As the DB changes inversely with the change of x, it can be said that increasing DB will decrease the core loss. However, the inclusion of high DB is not suggested because the high DB will produce high distortion at the output voltage of the core. This is why an optimized DB inclusion is mandatory for the core loss reduction and distortion minimization.

III. CORE CONSTRUCTION AND DEVELOPMENT

For the laboratory experiment and testing, first an optimized core is simulated in COMSOL Multiphysics software. After that, a prototype core is developed with the amorphous magnetic material. For the structural simplicity, a toroidal shaped core is processed. The inner and outer diameter of the core is chosen as 7.4 cm and 12 cm. The height of the core is 3 cm. For the construction of the core, an amorphous ribbon of 30 mm width and 28 μm thickness is utilized. The ribbons are glued together with Araldite 2011 for better mechanical and structural strength. The maximum saturation flux density, the curie temperature, the material density, and the resistivity of the amorphous material are 1.56 T, 410°C, 7.18 g/cm^3, and 130 μΩ cm respectively. The mass and volume of the core are 1.20 kg and 210.27 cm^3 respectively. A single layer winding of Litz wire is adopted on the primary and secondary sides of the core to tackle the skin and the proximity effect and to minimize the ac/dc resistance ratio of the conductor at HFs. In the primary and secondary sides, 12 and 10 insulated strands of copper wire (diameter 0.4 mm) are braided together respectively to form the Litz wire for the flux linkage equalization of the conductors. The number of turns on the primary and secondary side are 15 and 25 respectively.

IV. EXPERIMENTAL INVESTIGATION

For the experimental analysis and characterization, three major types of signals are taken into account, i.e. the square wave, the triangular, and the trapezoidal signals. The square wave signals are generated by the HF inverter based on the insulated gate bi-polar transistor (IGBT) module SK30GH123 from Semikron, driven by a SKHI 20opA isolated driver circuit. The gate pulses for the IGBT switches are generated from the TMS320F28335 Delfino microcontroller based digital signal processor board. The DB is included in the gate signals by appropriately programming the microcontroller. The triangular and trapezoidal signals are generated from the California Instruments CSW5550 programmable power supply as shown in Fig. 1(a). The secondary side voltage of the core is measured using the KEYSIGHT N2791A differential voltage probe and the primary

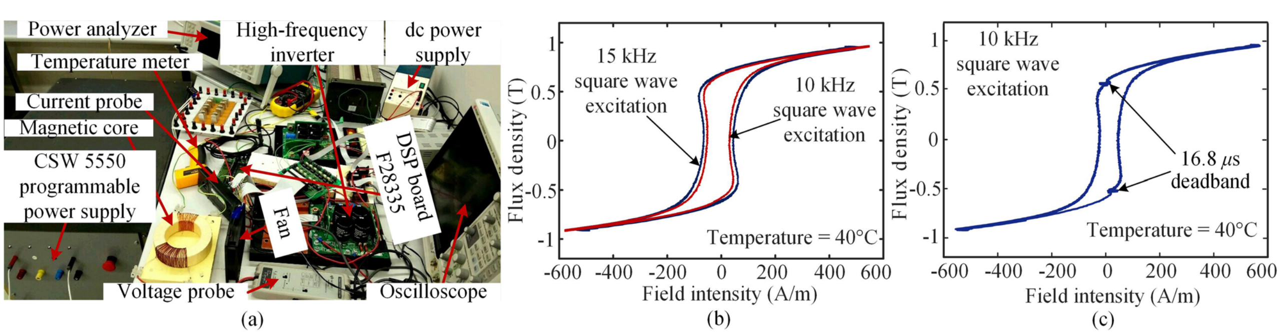

FIG. 1. (a) A photograph of the experimental setup, (b) B-H loops with 1 μs DB, and (c) B-H loop with 16.8 μs DB.

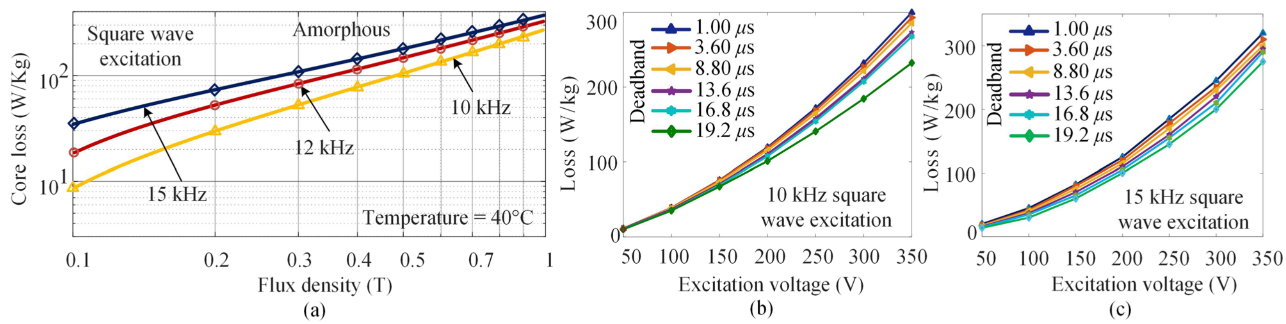

FIG. 2. Measured loss of the prototype core under high-frequency square wave signals: (a) losses under various flux densities ranging from 0.1 T to 1.0 T, (b) DB effect on the loss for 10 kHz square wave voltage, and (c) DB effect on the loss for 15 kHz square wave voltage.

side current is measured using the Agilent N2781A current probe. For the loss analysis and temperature measurement, the Tektronix PA4000 power analyzer and the FLUKE 62 IR thermometer are utilized respectively.

With the developed prototype core, the maximum flux density and the magnetizing current are measured to be 0.9 T and 4 A respectively. In Fig. 1(b), the measured *B-H* loops for the 10 and 15 kHz square wave signals are shown. With the increased frequency, the area of the loop is increased, which implies an increase in the core loss. The prototype core starts to saturate at 0.7 T and 160 A/m field intensity. The effect of including the DB in the square wave signals on the hysteresis loop is shown in Fig. 1(c). The B-H loop presents deviations due to the 16.8 μs DB. This distortion will increase with the increase of the DB. As shown in Fig. 2(a), for the fixed flux density of 0.7 T and a constant temperature, the specific losses for the prototype core are measured to be 97.8, 163.2, and 208.5 W/kg under 10, 12, and 15 kHz excitation voltages, respectively. Figs. 2(b)–2(c) exhibit the DB effect on the measured core loss. The results show that for 10 and 15 kHz excitation voltages, the inclusion of the DB decreases the core losses for a fixed excitation voltage. For example, the losses are measured as 172, 169, 164.7, 158, 154.2, and 140.8 W/kg for 1, 3.6, 8.8, 13.6, 16.8, and 19.2 μs DBs respectively, under a fixed voltage of 250V and a 10 kHz excitation frequency. A similar scenario can be noticed for a 15 kHz excitation voltage as shown in Fig. 2(c), though the specific losses are increased due to the increased frequency.

Attention must be paid before including the DB in the gate pulses. Although, it is found that the DB inclusion tends to decrease the losses, it also offers a high-level distortion at the output voltage of the core, which will eventually create problems at the circuitry connected at the output of the HFT. Experimental results reveals that with the increase of DB, the voltage and current waveforms experience higher distortion. For example, the weighted total harmonic distortion (WTHD) of the voltage waveforms is found to be 11.8, 13.35, and 21.67% for 1, 16.8, and 22.4 μs of DBs respectively. Additionally, the fundamental value of the voltage and current are decreased. Consequently, the specific core losses are decreased with the inclusion of DB. This observation highly agrees to the mathematical analysis stated in section II. Therefore, an optimization should be made between the DB and the loss before designing the magnetic core and HF inverter based system. It is observed from the experiment that for a DB of 8.8 μs in the 10 kHz square wave excitation, the output voltage and current of the prototype core do not experience much distortion and the DB can reduce the core loss to be slightly less than that when using a purely square wave excitation.

In recent power electronic based energy conversion systems, like three-phase dual active bridge converters or fly-back converters, the HFTs are excited with the trapezoidal or triangular signals depending on the size of the extra inductor connected with HFT. Therefore, for the complete characterization, the prototype core is further excited with 1, 2, and 4 kHz triangular and trapezoidal signals. The measured loss scenario is presented in Fig. 3. It can be

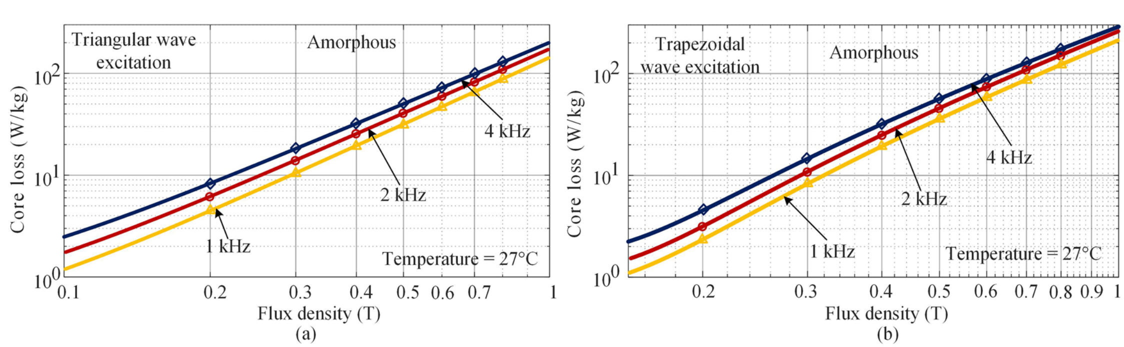

FIG. 3. Measured losses of the prototype core under non-sinusoidal voltage excitations: (a) triangular wave excitation and (b) trapezoidal wave excitation.

identified that the overall specific core losses at different flux densities are comparatively less for the triangular wave than that for the trapezoidal wave. For example, the losses are measured to be 60.5, 82.1, and 100.3 W/kg for the 1, 2, and 4 kHz triangular wave voltage excitations respectively at the constant flux density of 0.7 T. On the other hand, the losses are measured to be 85, 110, and 120 W/kg for the 1, 2, and 4 kHz trapezoidal wave voltage excitations at the constant flux density of 0.7 T. Moreover, Fig. 3 reveals that the core loss variations for different excitation frequencies are decreased at the high flux density region both for the triangular and the trapezoidal signal.

V. CONCLUSIONS

In this paper, an amorphous magnetic material-based prototype core is characterized under various high-frequency non-sinusoidal excitations. The effect of the DB from the HF inverter on the core loss is comprehensively analyzed and experimentally validated. It is found that for the fixed excitation voltage and frequency, the increase of the DB in the square wave signal will decrease the specific core loss. However, a higher DB causes higher distortion at the output voltage and corresponding magnetizing current of the core. This higher distortion puts a heavy burden on the output rectifying circuitry when the core is used in a high-frequency energy conversion circuit. Therefore, an optimized DB needs to be designed so that the distortion effect, i.e. the percentage of WTHD, and the core loss can be minimized. Furthermore, the characterization of the core is carried out under the HF triangular and the HF trapezoidal signals. The experimental results show that for a fixed frequency excitation and temperature, the specific core losses are greater for the trapezoidal signal than that for the triangular signal.

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